Inclusive dielectron production in proton-proton collisions at 2.2 GeV beam energy

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Data on inclusive dielectron production are presented for the reaction $p+p$ at 2.2 GeV measured with the High Acceptance DiElectron Spectrometer (HADES). Our results supplement data obtained earlier in this bombarding energy regime by DLS and HADES. The comparison with the 2.09 GeV DLS data is discussed. The reconstructed e^+e^- distributions are confronted with simulated pair cocktails, revealing an excess yield at invariant masses around 0.5 GeV/c^2. Inclusive cross sections of neutral pion and eta production are obtained.

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I. INTRODUCTION

The spectroscopy of e^+e^- pairs offers a new approach to the study of baryon resonances excited in nucleon-nucleon reactions. Dilepton (that is e$^+$e$^-$ or $\mu^+\mu^-$) observables provide indeed information on the electromagnetic structure of the resonances and, in the context of vector meson dominance, their coupling to the light vector mesons [1]. Furthermore, dilepton spectroscopy allows to study the properties of hadrons produced and decayed in a strongly interacting medium. This is because leptons do not themselves interact strongly when propagating through hadronic matter, that is, their kinematics remains basically undistorted. For that reason they are used to probe medium modifications of hadrons intensively searched for in photon and proton-induced

reactions on nuclei as well as in heavy-ion collisions [2]. Transport models are commonly employed to describe particle production and propagation through the medium, in particular when dealing with the complex dynamics of nucleus-nucleus reactions [3–5]. The proper modeling of lepton pair production mechanisms requires a solid understanding of the underlying elementary processes, be it in terms of resonance excitations or in terms of a string fragmentation picture [6].

The HADES experiment pursues a comprehensive program of dielectron emission studies in $N+N$ [7, 8], in $p+A$ [9], as well as in $A+A$ collisions [10–12]. Inclusive e^+e^- production in $p+p$ and $p+d$ reactions had formerly been studied in the range of 1 - 5 GeV by the DLS experiment at the Bevalac [13], and more recently by HADES at 1.25 GeV [7] and 3.5 GeV [8]. In particular, the comparison of the latter data sets with various model calculations demonstrated a need for improved theoretical descriptions. In this paper we supplement the available body of experimental results with data obtained on inclusive e^+e^- production in the $p+p \to p+p+e^++e^-+X$ reaction at 2.2 GeV. A direct comparison with DLS data measured at 2.09 GeV [13] is presented. Furthermore, through the comparison with a calculated e^+e^- cocktail, we extract the inclusive production cross sections of π^0 and η mesons at 2.2 GeV. Our paper is organized as follows: Section 2 describes the experiment and the data analysis. In Sec. 3 e^+e^- pair spectra are presented and confronted with results from DLS. In Sec. 4 the pair spectra are compared to calculated dielectron cocktails. In Sec. 5 we discuss inclusive meson production cross sections and, finally, in Sec. 6 we summarize our findings.

II. THE EXPERIMENT

The six-sector High-Acceptance DiElectron Spectrometer (HADES) operates at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt taking beams from the heavy-ion synchrotron SIS18. Technical aspects of the detector are described in [14]. Its main component serving for electron and positron selection is a hadron-blind Ring-Imaging Cherenkov detector (RICH). Further particle identification power is provided by the time of flight measured in a plastic scintillator wall (TOF), the electromagnetic shower characteristics observed in a pre-shower detector, and the energy-loss signals from the scintillators of the TOF wall.

In the experiment discussed here [15] a proton beam with a kinetic energy of $T_p = 2.2$ GeV (corresponding to a c.m. energy $\sqrt{s_{NN}} = 2.765$ GeV) and an intensity of about 10^7 particles per second impinged on a 5 cm long liquid hydrogen cell with a total areal thickness of 0.35 g/cm^2. The online event selection was done in two steps: (1) a 1^{st}-level trigger (LVL1) selected events with an overall multiplicity of at least four charged hits in the TOF wall with additional topological conditions (two opposite sectors hit, two hits at polar angles $< 45°$), and (2) a 2^{nd}-level trigger (LVL2) required an electron or positron candidate. This trigger scheme was in fact optimized for measuring exclusive e^+e^- production in the $p+p \to p+p+\eta$ reaction with a subsequent η Dalitz decay [16]. Note that such a trigger condition still allows to study, albeit with a bias, inclusive e^+e^- emission. Indeed, because of overall charge conservation in the $p+p$ reaction, the dielectron is always accompanied by at least two more charged particles. The resulting trigger bias has been studied in simulations as a function of various pair observables, in particular pair mass and pair transverse momentum, providing a correction as well as an estimate of the resulting systematic error (of order 20%). For normalization purposes, $p+p$ elastic scattering events were recorded concurrently with an additional scaled-down (by a factor 32) LVL1 trigger condition requiring only two charged hits in opposite HADES sectors. Thus, in total 2.7×10^8 LVL1 events were recorded, 4.1×10^7 of which fulfilled the LVL2 condition.

Dielectrons (that is e$^+$e$^-$ pairs) were reconstructed following the procedures described in detail in [11, 14]: (1) leptons were identified based on various detector observables, (2) an efficiency correction was applied, (3) opposite-sign leptons were combined into pairs, (4) the background of uncorrelated (and partially correlated) pairs representing the combinatorial background (CB) was subtracted using the same-event geometric mean of like-sign pairs, (5) the correction for the LVL1 trigger bias was applied, and finally (6) the resulting inclusive e^+e^- distributions were normalized to the reconstructed yield of elastically scattered protons into the HADES geometric acceptance (see [16] for details). As no dedicated start detector was present in this experimental run, the start time for the time-of-flight measurement was reconstructed event-by-event from the most optimal fit of different event hypotheses to the global event data [16].

III. RESULTS

A. Invariant mass spectra

Figure 1 shows the differential e^+e^- cross section $d\sigma/dM_{ee}$ obtained after correcting the reconstructed pair yield for efficiency, combinatorial background, and trigger bias. As explained above, the absolute normalization was done using the known $p+p$ elastic scattering cross section with the help of the concurrently measured yield of elastic events [16]. The data are presented with analysis cuts on single-lepton momentum, $p_e > 0.1$ GeV/c, and on pair opening angle, $\theta_{ee} > 9°$. The total number of e^+e^- signal pairs contributing to this spectrum is around 19,000 from which 2,000 pairs are located above the π^0 Dalitz region ($M_{ee} > 0.15$ GeV/c^2). To illustrate the significance of the reconstructed dielectron signal, the signal-over-CB ratio is also shown as an inset in Fig. 1. Note that the kinematic cutoff corresponding to the beam energy of 2.2 GeV is at a pair mass of 0.89 GeV/c^2.

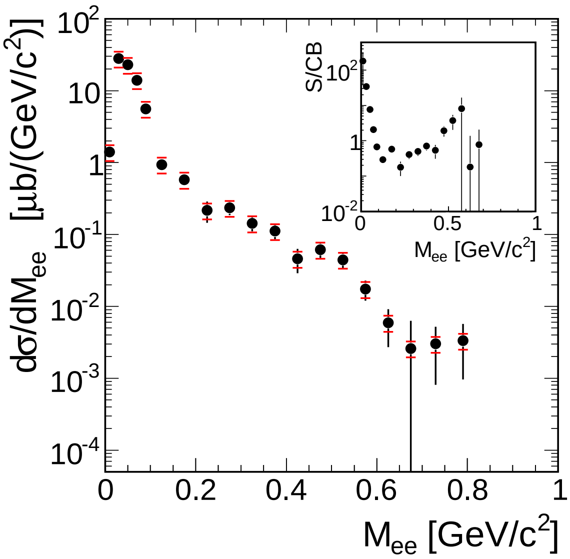


FIG. 1: (Color online) Differential e^+e^- cross section $d\sigma/dM_{ee}$ measured in the 2.2 GeV $p + p$ reaction within the HADES acceptance (including $p_e > 0.1$ GeV/c and $\theta_{ee} > 9°$ cuts). The data are efficiency corrected and CB subtracted; the insert shows the signal-over-CB ratio (S/CB). Point-to-point statistical and systematic errors are indicated by (black) vertical bars and (red) horizontal ticks, respectively.

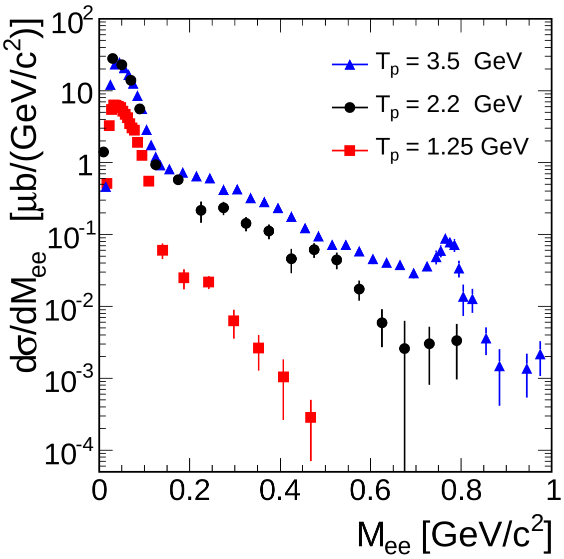


FIG. 2: (Color online) Systematics of e^+e^- differential production cross sections $d\sigma/dM_{ee}$ measured in $p + p$ reactions at 1.25 GeV (squares), 2.2 GeV (circles), and 3.5 GeV (triangles), all obtained within the HADES acceptance, efficiency corrected, and CB subtracted (including $p_e > 0.1$ GeV/c and $\theta_{ee} > 9°$ cuts). The 1.25 GeV data, taken from [7], are adjusted for the present, more restrictive detector acceptance (i.e. stronger magnetic field and explicit lepton momentum cut of 0.1 GeV/c); the 3.5 GeV data are taken from [8]. Only statistical error bars are shown.

The obtained cross section is combined in Fig. 2 with inclusive data from other HADES $p + p$ runs done at 1.25 [7] and 3.5 GeV [8] bombarding energy, respectively. While the 3.5 GeV data were recorded in the same detector acceptance as the present 2.2 GeV data, the 1.25 GeV data were adjusted for differences in the magnetic field strengths and analysis cuts used. This way the three data sets are compared within the same instrumental acceptance, revealing the strong beam energy dependence of dielectron production, particularly at large pair masses. Note, however, that between the three beam energies the average momentum of the involved single lepton distributions differs significantly, resulting in substantially different fractions of accepted pairs, particularly for low masses.

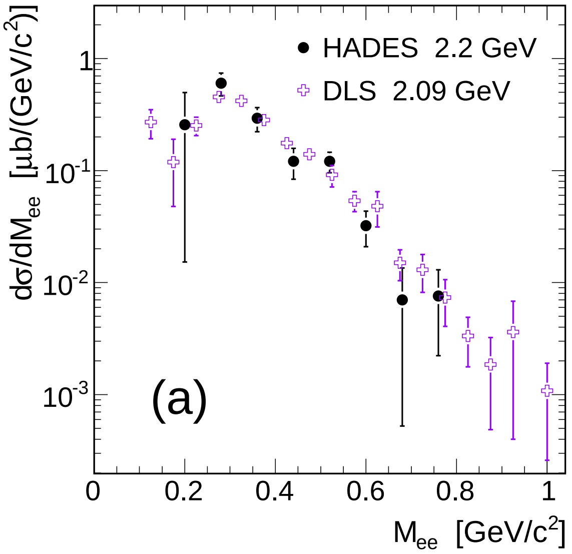
B. Comparison with DLS

As the former DLS experiment provided e^+e^- data for the $p+p$ reaction at 2.09 GeV [13], we can make a direct comparison along the line already used to confront the DLS and HADES C+C data obtained at 1A GeV [10, 17]. As the HADES geometrical acceptance is substantially broader than the DLS one such a comparison can be done by projecting the reconstructed HADES dielectron yields $d^3N/dM_{ee}dP_\perp dY$ through the DLS acceptance filter [17] (here $P_\perp$ and Y are the e^+e^- pair transverse momentum and rapidity, respectively). In fact, as DLS applied to their $p + p$ data additional cleaning cuts [13, 18] – $0.1 < M_{ee} < 1.25$ GeV/c^2, $P_\perp < 1.2$ GeV/c, $0.5 < Y < 1.7$, and $\theta_e > 21.5°$ – an extrapolation of the HADES yield to rapidities above 1.9, as applied in [10], is not needed here. The result of this filtering procedure is shown in Fig. 3(a) for the pair mass distributions $d\sigma/dM_{ee}$ and in (b) for the pair transverse momentum spectrum $1/(2\pi P_\perp)\, d\sigma/dP_\perp$, the latter one with the condition $M_{ee} > 0.15$ GeV/c^2.

It is apparent that, within statistical and systematic uncertainties, the HADES and the DLS data are in good agreement. This result suggests that our result, together with the data obtained by the DLS energy scan [13], can be used to constrain the various models aimed at describing dielectron production in few-GeV elementary reactions [8].

IV. COMPARISON WITH A SIMULATED COCKTAIL

The experimental pair distributions are next compared to a calculated e^+e^- cocktail. For this, $p + p$ reactions were simulated with the event generator Pluto [19, 20] and filtered through the HADES acceptance. The sim-



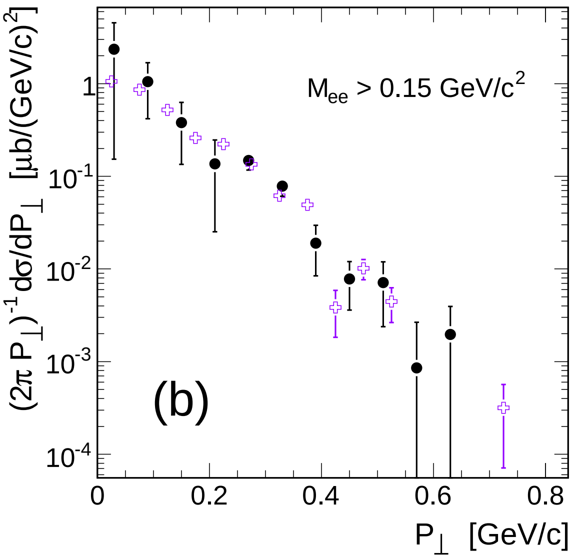


FIG. 3: (Color online) Direct comparison within the DLS acceptance (see text for details) of the e^+e^- cross sections measured by HADES in $p+p$ at 2.2 GeV (closed circles) and by DLS at 2.09 GeV (open crosses, taken from [13]). The pair mass distributions (a) and pair transverse-momentum distributions (b) are confronted. Error bars are statistical only; additional systematic errors (not shown) are 23% for DLS [13] and 29% for HADES.

ulation included the following e^+e^- pair sources: (1) $\pi^0 \to \gamma e^+e^-$, (2) $\eta \to \gamma e^+e^-$, (3) $\Delta(1232) \to Ne^+e^-$, (4) $\omega \to \pi^0 e^+e^-$, (5) $\omega \to e^+e^-$, and (6) $\rho^0 \to e^+e^-$ with dielectron branching ratios of mesons taken from [21] and that of the $\Delta(1232)$ as calculated in [1]. At the present bombarding energy the production of π^0 and η mesons is known to proceed mostly via resonance excitation (e.g. $R = \Delta(1232), N^*(1440), N^*(1520), N^*(1535)$, etc.) and is dominated by one-meson and two-meson channels [16, 22–24]. For ρ^0 and ω production we have, however, assumed phase-space population in the $pp \to ppX$ reactions ($X = \rho^0$ or ω) with no further attempt at a more refined description of the high-mass region. Note that some of the excited resonances R, mostly the Δ, contribute also directly to the dielectron yield via their electromagnetic Dalitz decay $R \to Ne^+e^-$. In our cocktail calculation we have only taken into account the Δ^0 and Δ^+ contributions following the prescription from Ref. [8]. The production cross sections used in the simulation were taken as follows:

1. Inclusive π^0 production – 14 mb (adding all observed inelastic channels contributing to π^0 production from Ref. [25] gives a lower limit of about 12 mb, whereas 14 mb are needed to fully exhaust the measured Dalitz yield).

2. Inclusive η production – in the range of 0.26 - 0.35 mb; a lower limit of 0.14 mb is given by the known exclusive η production [16, 26].

3. Vector meson production – 0.01 mb exclusive ω production [27] and assuming likewise for the ρ^0, but no ϕ contribution.

4. Inclusive $\Delta^{0,+}(1232)$ excitation – in the range 10 - 21 mb.

The extremes of the cross section range used for Δ production correspond to the following two scenarios: (I) assumes that pion production is mediated completely by single Δ excitation only, that is $\sigma_\Delta = 3/2\,\sigma_{\pi^0}$ (from isospin addition rules), resulting in the upper value of 21 mb; scenario (II) sums explicitly the Δ contributions from one-pion and two-pion production channels. In the latter the one-pion part of 3.6 mb is taken from a resonance model fit to exclusive pion production data [16] whereas the two-pion part of 6.4 mb is taken from the effective Lagrangian model of two-pion production presented in Ref. [24]. Under the assumption and as suggested indeed by various calculations [3–5] that dielectron production is dominated in the mass range 0.15 - 0.45 GeV/c^2 by the Δ and η contributions, the total yield measured for these masses can be used to constrain the η contribution for any assumed Δ cross section. In other words, the η and Δ contributions are complementary. The extracted η cross section will evidently have a model dependence which, however, turns out to be small.

The resulting e^+e^- cocktails, filtered with the HADES acceptance, are overlayed in Figs. 4 and 5 with the data. Up to masses of $\simeq 0.45$ GeV/c^2 the agreement is good in both observables, M_{ee} and $P_\perp$, although at higher masses the measured yield is not matched. Integrating up to 0.15 GeV/c^2 the low-mass region, dominated evidently by the π^0 Dalitz contribution, and correcting for the detector acceptance, allows to fix the inclusive π^0 production cross section at $\sigma_{\pi^0} = 14 \pm 3.5$ mb. The quoted 25% error is determined mostly by systematic effects (normalization, trigger bias correction, acceptance correction).

In a similar way, the integrated yield from the mass region of 0.15 - 0.45 GeV/c^2 has been used to extract the cross section of inclusive η production after correcting, as stated above, for the Δ contribution. The range of assumed Δ cross sections used in the simulation leads consequently to a corresponding range of η production cross sections, indicated by the hatched bands shown in the two figures. In scenario (I), where all π^0 production goes through Δ excitation and decay, $\sigma_\Delta = 21$ mb and $\sigma_\eta = 0.26$ mb. In scenario (II), based on the model of [24], various nucleon resonances contribute to pion production, such that $\sigma_\Delta = 10$ mb and $\sigma_\eta = 0.35$ mb. We feel that this model dependence is relatively small and propose to use the average of the two results, namely $\sigma_\eta = 0.31 \pm 0.08 \pm 0.05$ mb, where the first error is again mostly ruled by systematic effects (normalization, trigger bias and acceptance corrections) while the second one covers the model dependence.

In the pair mass range 0.45 - 0.60 GeV/c^2 our simulation underestimates grossly the observed yield. This is also visible in the comparison of transverse momentum distributions shown on Fig. 5. Clearly additional dielectron sources are needed, among which one has to consider the decays of N^* resonances, e.g. the $N^*(1520)$ and $N^*(1720)$ known to couple strongly to the ρ, as well as a possible general enhancement due to vector meson dominance form factors of the nucleon resonances [1].

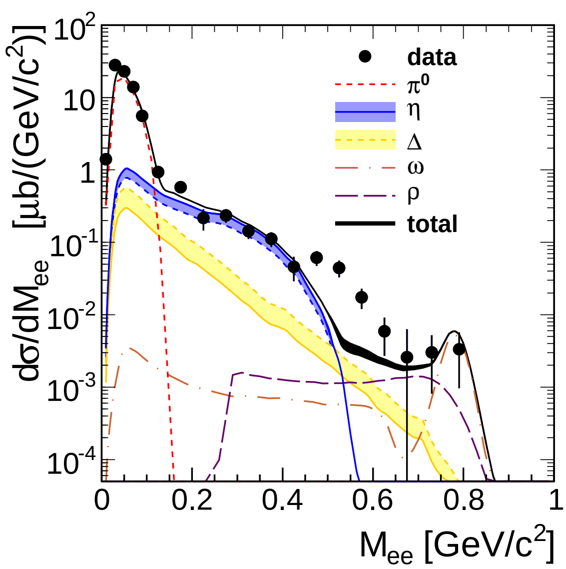


FIG. 4: (Color online) Pair mass distribution $d\sigma/dM_{ee}$ measured in 2.2 GeV $p+p$ reactions (full circles) compared with simulated Pluto [19, 20] cocktails of dielectron sources filtered through the HADES acceptance. The shaded bands delimit the range of modeled Δ and η contributions – as discussed in the text – with the dashed delimiters corresponding to scenario (I) and the solid ones to scenario (II). Only statistical errors are shown.

V. INCLUSIVE MESON PRODUCTION

The inclusive π^0 and η production cross sections obtained in the present analysis can be combined with the result from our $p+p$ runs at 1.25 and 3.5 GeV to investigate the excitation function of meson production in the few-GeV regime. Figure 6 shows these cross sections as function of $\sqrt{s_{NN}}$ together with exclusive data. A wealth of information on exclusive pion production in nucleon-nucleon reactions has indeed been accumulated over the past 50 years (see [22, 23] for reviews and [25] for a compilation). Fits to exclusive π^0 production cross sections in one-pion and two-pion channels from [22] are shown in Fig. 6. These processes are quite well understood in terms of nucleon resonance excitations within the resonance models [22, 24]. Data on π^0 production involving three or more pions in the final state is, however, still scarce and incomplete, although such processes can be expected to contribute substantially at beam energies above a few GeV. Indeed, from an extrapolation of three-pion production data to $T_p = 2.2$ GeV published recently [28] it is estimated that the contributions of the $\pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$ channels could add up to as much as 0.5 mb. Figure 6 shows in fact very clearly that around 2.2 GeV bombarding energy inclusive pion production stops to be fully exhausted by the sum of one- and two-pion channels only.

Turning to η production we can do a similar comparison. Here, data has again been only available for the exclusive channel. A compilation of exclusive η production cross sections (from [23], extended with recent HADES results [16]) is depicted in Fig. 6, as well as the corresponding resonance model calculation of Teis *et al.* [29]. Assuming that η production is mediated solely by the $N^*(1535)$ resonance, the latter gives a reasonable description of the data. Just like in the case of pion production, our inclusive cross sections largely exceed the exclusive ones in the energy range investigated here. Because a microscopic description of multi-particle production is not yet at hand, transport models often make use of cross section parameterizations based on the Lund string fragmentation model (LSM) [6]. Sibirtsev's parameterization of η production [30], based on the LSM and shown as dot-dashed line in Fig. 6, turns out to be in reasonable agreement with our inclusive result, although the intended validity range of the LSM is in fact at much higher beam energies.

VI. SUMMARY

To summarize, we have presented data on inclusive e^+e^- production in the reaction $p+p$ at 2.2 GeV beam kinetic energy. The measured dielectron cross sections are in good agreement with the DLS result obtained earlier at 2.09 GeV. The employed cocktail of e^+e^- sources does not saturate our data at invariant mass around 0.55 GeV/c^2. Furthermore, inclusive π^0 and η produc-

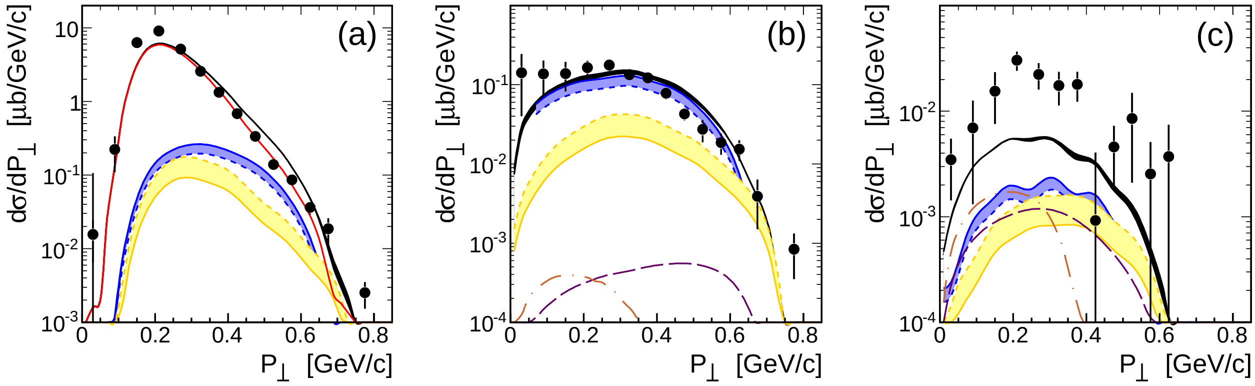


FIG. 5: (Color online) Pair transverse momentum distributions $d\sigma/dP_{\perp}$ measured in 2.2 GeV $p+p$ reactions within the HADES acceptance. Three mass bins are shown: (a) $M_{ee} < 0.15$, (b) $0.15 < M_{ee} < 0.45$, and (c) $M_{ee} > 0.45$ GeV/c^2. The simulated Pluto cocktails are shown as well, with line styles as in Fig. 4.

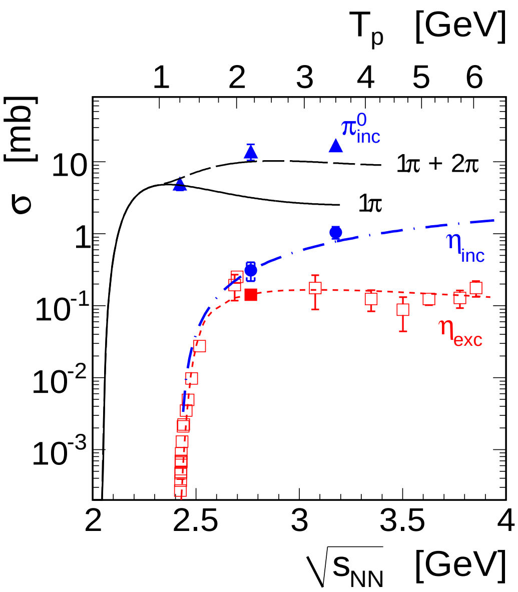


FIG. 6: (Color online) π^0 and η production cross sections in $p+p$ reactions as a function of the c.m. energy $\sqrt{s_{NN}}$ (bottom scale) and beam kinetic energy T_p (upper scale). The present inclusive results are shown as full triangles and circles, respectively, together with more HADES data obtained at bombarding energies of 1.25 GeV [7] and 3.5 GeV [8]. Fits to a compilation of 1π and $1\pi + 2\pi$ cross sections [22] are shown as solid and long-dashed curves, respectively. Open squares are η exclusive cross sections taken from [23, 25]; the solid square is the exclusive HADES point from [16]. The short-dashed curve corresponds to the resonance model [29], and the dot-dashed curve is the parametrization of inclusive η production from [30].

tion coss sections were deduced, extending the world body of meson production data. Such data, besides having their own interest in the context of medium-energy hadron reactions, represent valuable input for the analysis and simulation of proton-nucleus and heavy-ion collisions in the same energy regime.

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